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Variability of Power from Distributed Wind Facilities in Montana

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Project History

- December 2005: Invenergy Judith Gap Commissioning
- April 2006: NWE encounters first performance violation
- Fall 2006: NWE procures regulating service
- Spring 2007: NWE and wind industry approaches GENIVAR

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Project Overview

Part 1: Wind Power Variability Analysis

- Wind data collected from participating developers
- 3 wind development scenarios capture effect of future development plans (as proposed)
- 3 wind development scenarios capture effect of geospatial distribution (hypothetical)
- Results from all 6 scenarios presented here

Part 2: NWE Dispatch Simulation

- The Alberta Electric System Operator (AESO) developed a system dispatch time-simulator
- GENIVAR adapted the simulator from AESO’s operating parameter to NWE’s
- Impact of all 6 wind development scenarios on system operations were evaluated
- Wind forecasting and additional regulating reserves were explored as mitigating measures

Part 1: Wind Power Variability Analysis

Objective

- Simulate 10 minute wind power time series for a facility – GENIVAR Variability Model
- Simulate 1 minute wind power time series for a facility – Statistical approach
- Summarize variability of both 1-minute and 10-minute series

Significance

- Variability statistics developed for various growth scenarios
- Variability statistics developed for various geographical dispersion scenarios
- Simulated 1-minute wind power is input to the NWE Dispatch Simulation to asses grid operation impact

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Part 1: Wind Power Variability Analysis

- Model Inputs
  - Wind speed measured at proposed development sites
  - A standard power curve for a single turbine
  - Nameplate capacity of the facility
  - Dimension of the facility

Part 1: Wind Power Variability Analysis

Methodology

- Per Norgard and Hannele Holttinen, A Multi-Turbine Power Curve Approach. Proceedings of Nordic Wind Power. Conference NWPC, 2004
- Moving Average Wind Speed
- Multi Turbine Power Curve
- Adjust annual power production
- Apply weighted moving average wind speed to Multi-Turbine Power curve for 10-minute power time series
- 1-minute power time series modeled
- Time series of individual facilities combined to generate state-wide development scenarios
- Inspect time series and summarize variability

Part 1: Wind Power Variability Analysis

- Validation
  - Validation was not performed for Montana
  - Extensive validation performed for Alberta
  - Facility Validation
  - Regional Validation

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Part 1: Wind Power Variability Analysis

Scenario Description

- Historical: Scenario A (for dispatch model validation only)
- Proposed Future Developments:
  - Scenarios were based on projected on-line dates of projects under development, regardless of locations within the state
  - Scenario B: 358.5MW, includes Scenario A plus at least 3 new projects (more dispersion than A)
  - Scenario C: 741MW, includes Scenario B plus at least 3 new projects (more dispersion than B)
  - Scenario D: 1450MW, includes Scenario C plus at least 3 new projects (less dispersion than C)
- Hypothetical Developments: Scenario E, Scenario F, Scenario G
  - Designed to capture advantage of regional diversity

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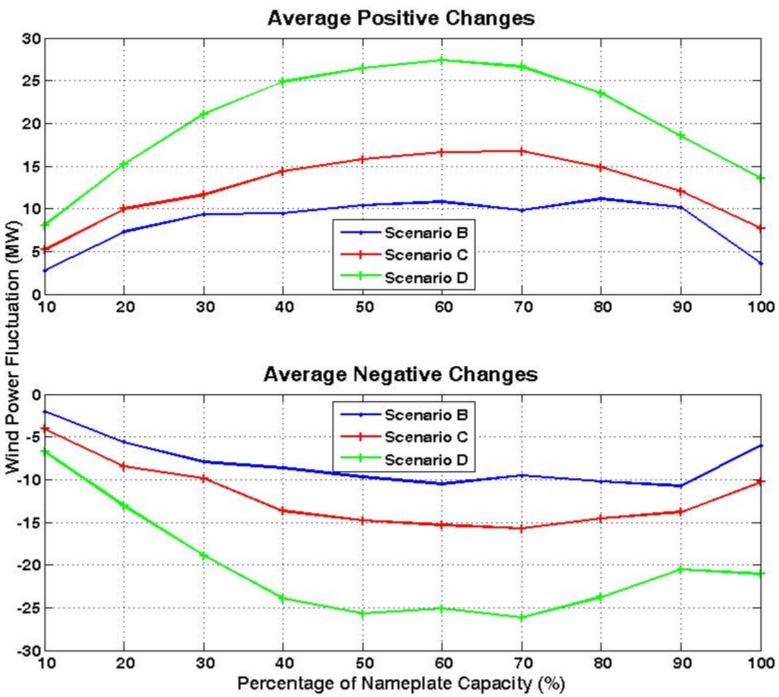
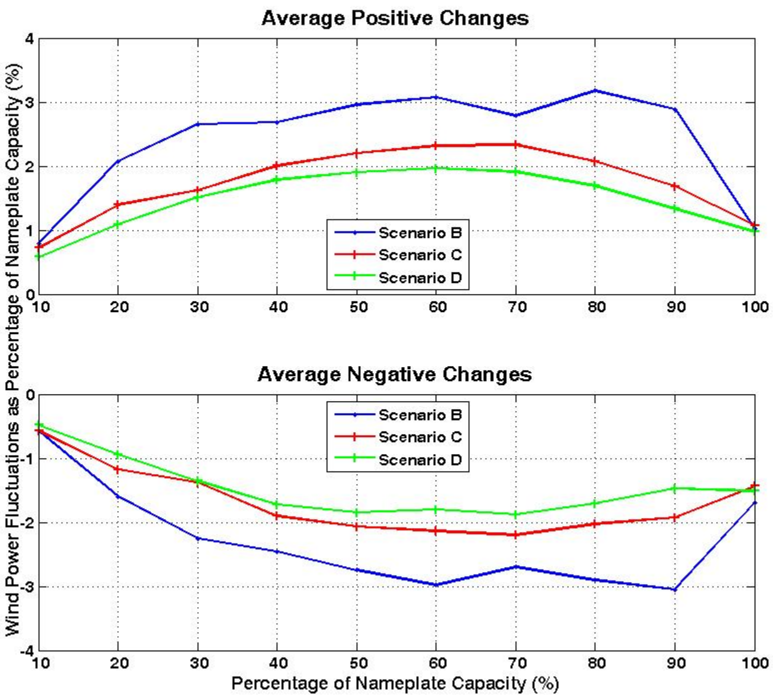
Part 1: Wind Power Variability Analysis

- Results: Proposed Scenarios, 10-minute model





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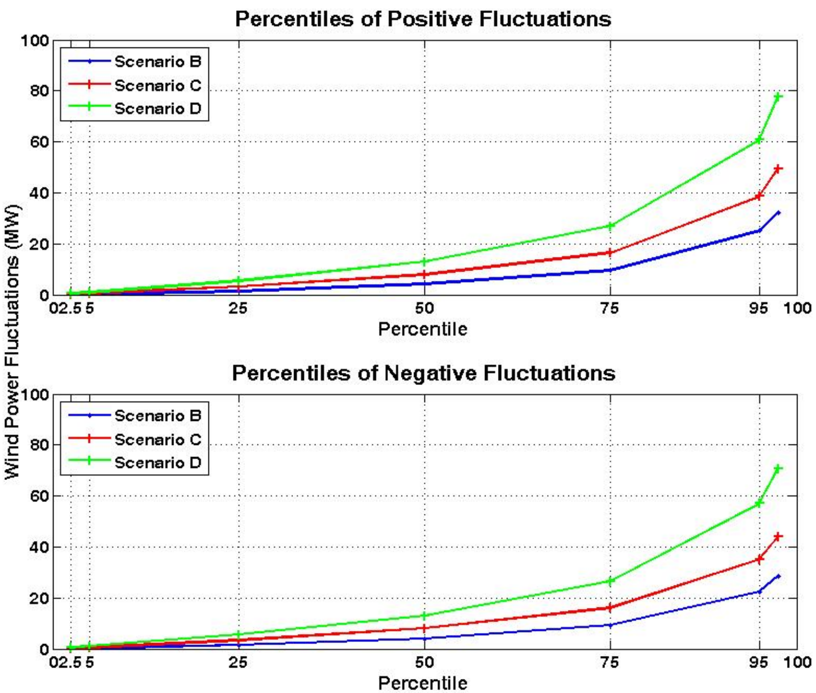

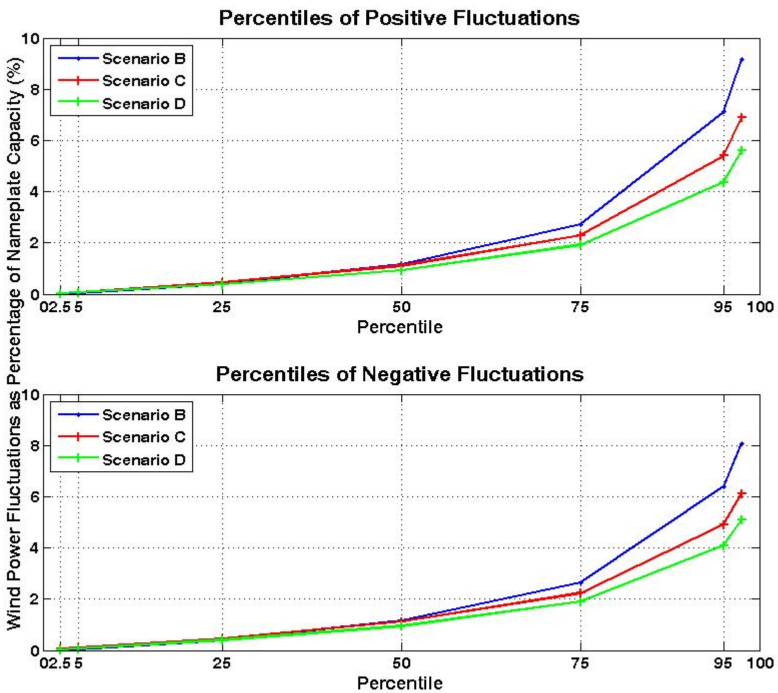

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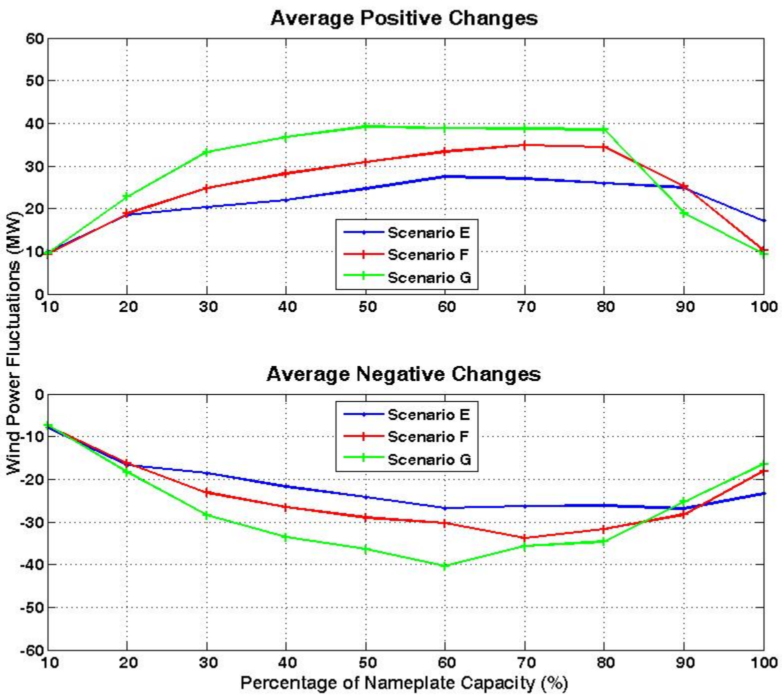
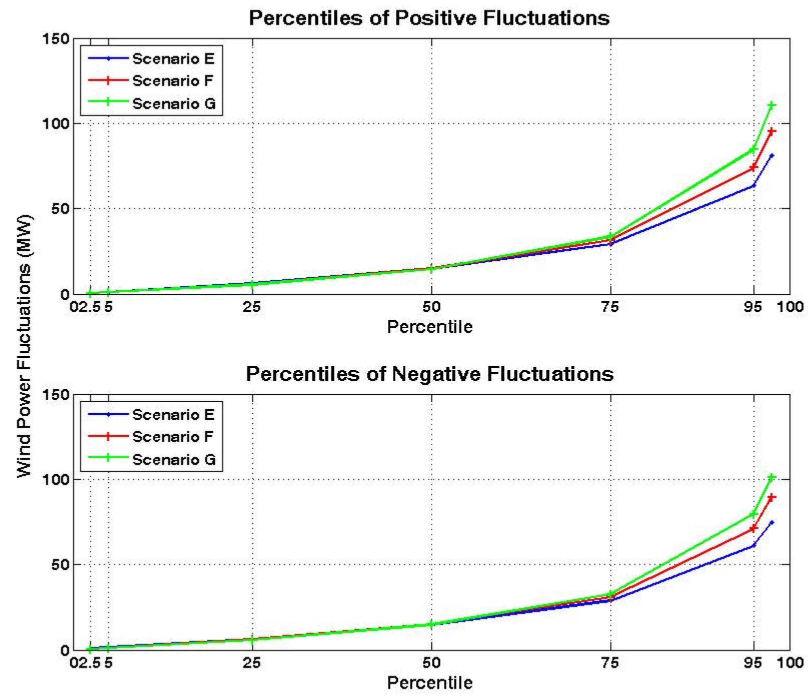
Part 1: Wind Power Variability Analysis

↗ Results: Hypothetical Scenarios, 10-minute model





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Part 2: NWE Dispatch Simulation

- **Objective**
  - Simulate NWE method of system dispatch
  - Input simulated wind power from Part 1 while maintaining same dispatch methods. Assess impact of additional wind power
  - Evaluate mitigation methods: wind power forecasts and additional regulating reserves
- **Significance**
  - Guide NWE in planning for new wind power installations
- **Challenge**
  - Adapting original AESO model to capture NWE system operations

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Part 2: NWE Dispatch Simulation

- **Model Inputs**
  - Simulated Wind Power
  - Historical system load, load forecast, and interchange schedule
  - NWE System operational parameters (including regulating range and rates, conventional generation capacity and rates, interchange schedule and limits)

Part 2: NWE Dispatch Simulation

Methodology

- Methodology developed by Alberta Electrical System Operator (AESO)
- Overall simulation approach maintained but specific algorithms were adapted to reflect NWE operations
- Validate by running simulation with historical data and comparing to actual performance
- Establish Benchmark: historical system data with current regulating and interconnect capacities
- Evaluate system response for all 6 wind development scenarios
- Evaluate wind forecasting as a mitigation method
- Evaluate increased regulation capacity as a mitigation method

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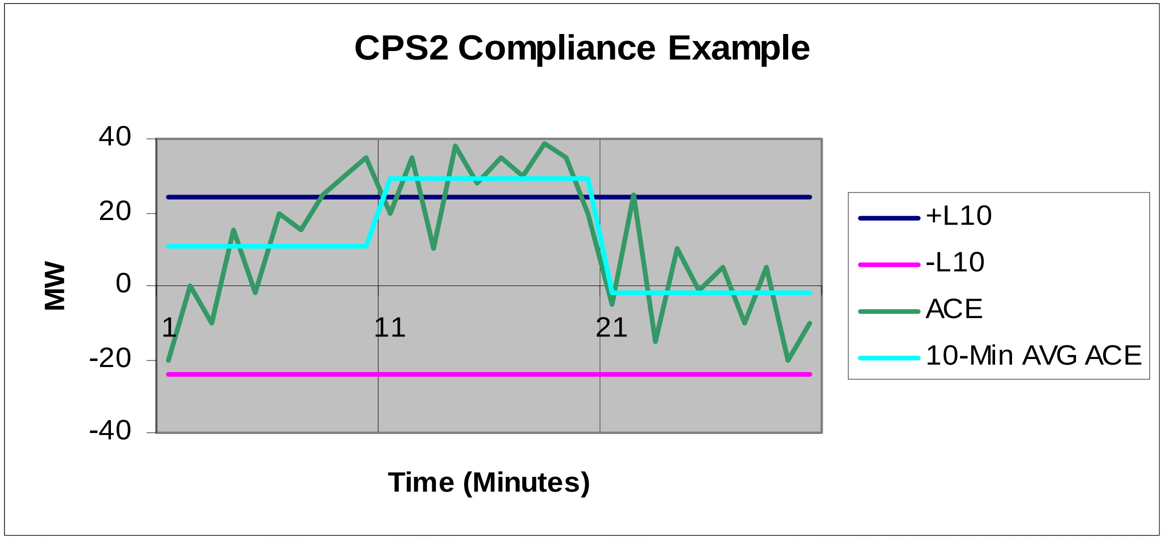
Part 2: NWE Dispatch Simulation

Performance Standards Definition

- ACE: Area Control Error is the instantaneous discrepancy between supply and net demand; which can be equally quantified as the difference between actual interchange and scheduled interchange.
- CPS2: a statistical measure designed to limit unacceptably large net unscheduled power flows.
- The following chart shows the ACE, L_{10} band, and average ten-minute ACE for a 30 minute period. The second ten-minute average is in violation since it exceeds L_{10}.



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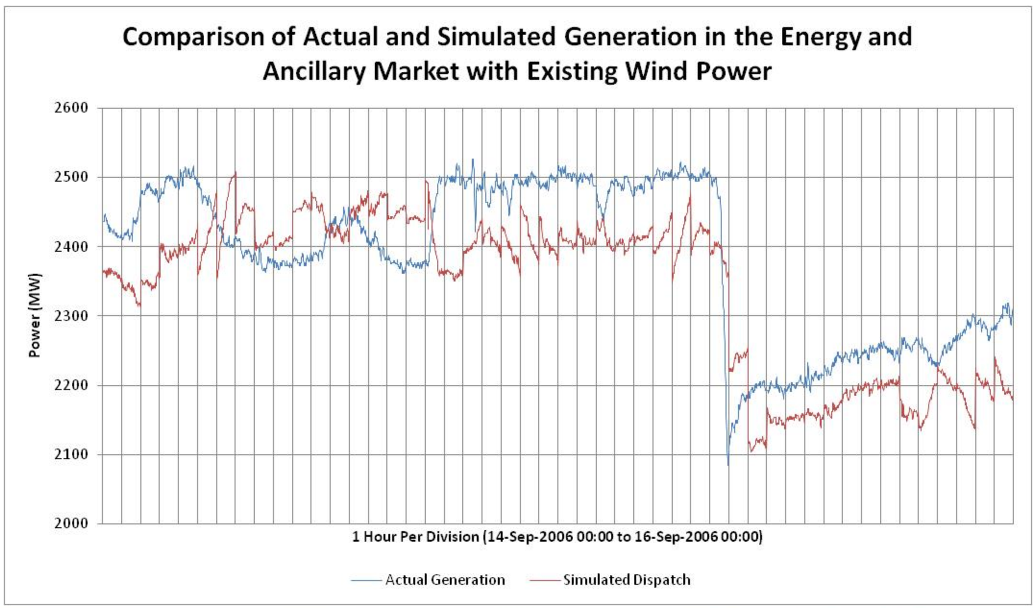
Part 2: NWE Dispatch Simulation

- Dispatch Simulation Validation
  - Time Series comparison of simulated and historical energy dispatch



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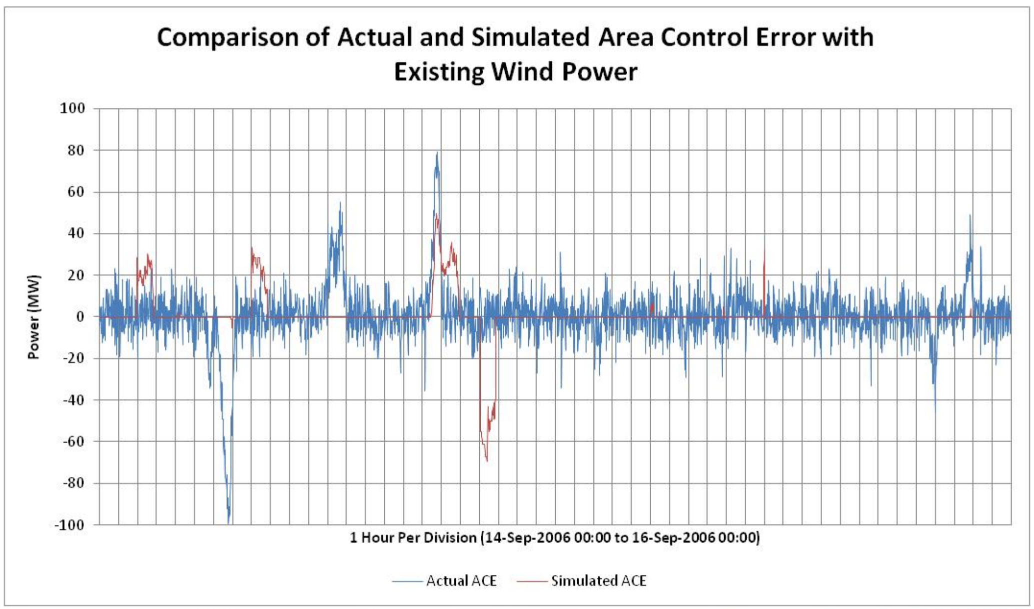
Part 2: NWE Dispatch Simulation

Dispatch Simulation Validation

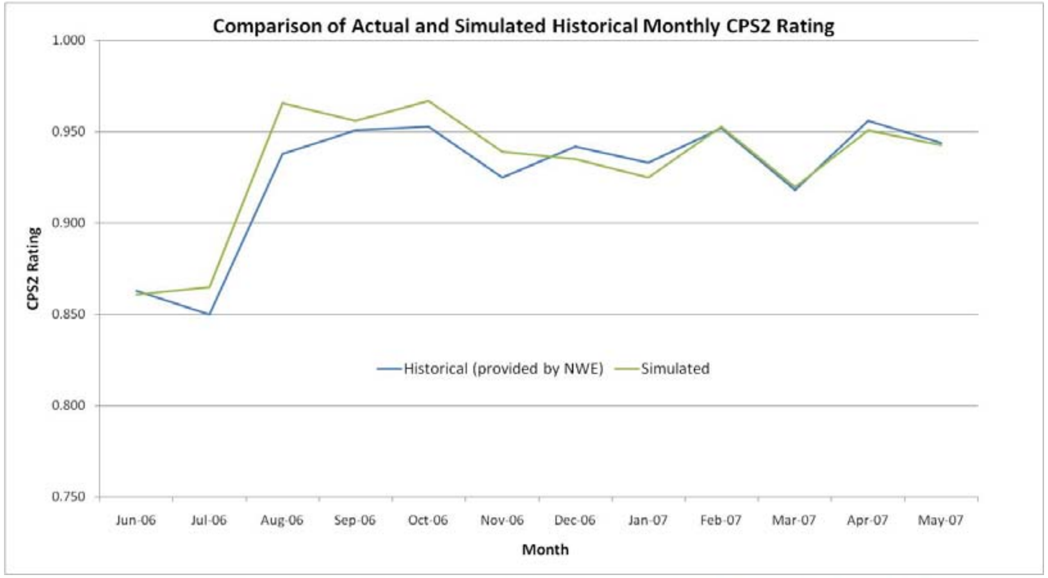
- Time Series comparison of simulated and historical energy dispatch
- Time Series comparison of simulated and historical ACE



Part 2: NWE Dispatch Simulation

Dispatch Simulation Validation

- Time Series comparison of simulated and historical energy dispatch
- Time Series comparison of simulated and historical ACE
- Comparison of simulated and Historical CPS2



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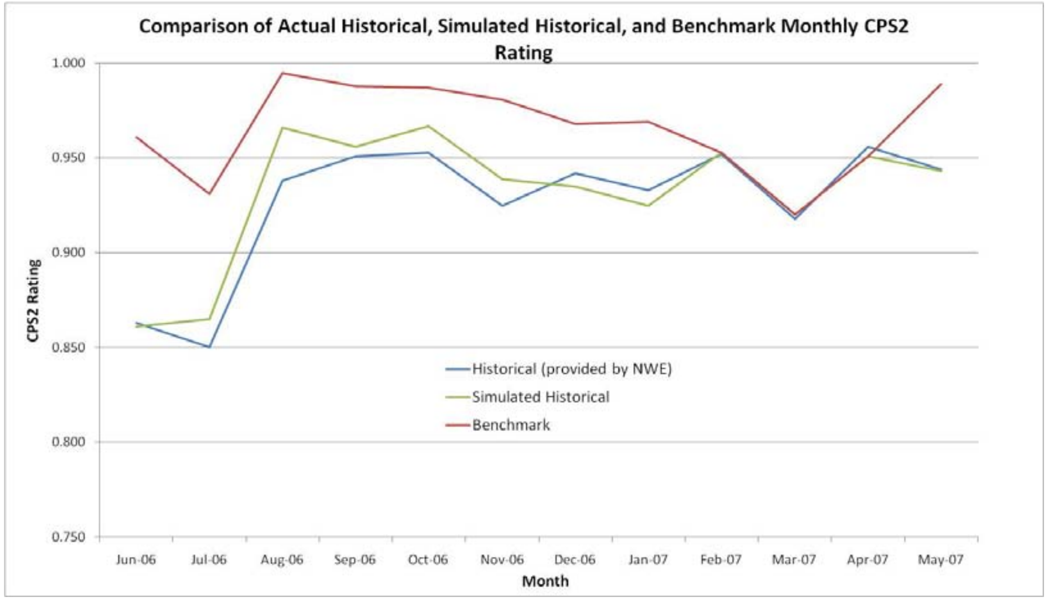
Part 2: NWE Dispatch Simulation

Dispatch Simulation Results

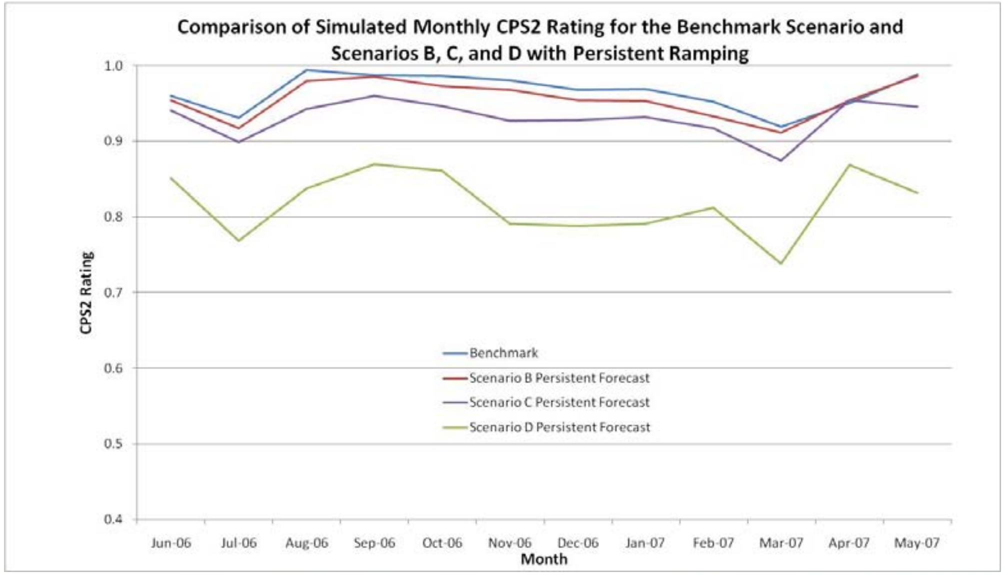
- Benchmark Scenario was established: historic wind development but current regulating capacity



Part 2: NWE Dispatch Simulation

Dispatch Simulation Results

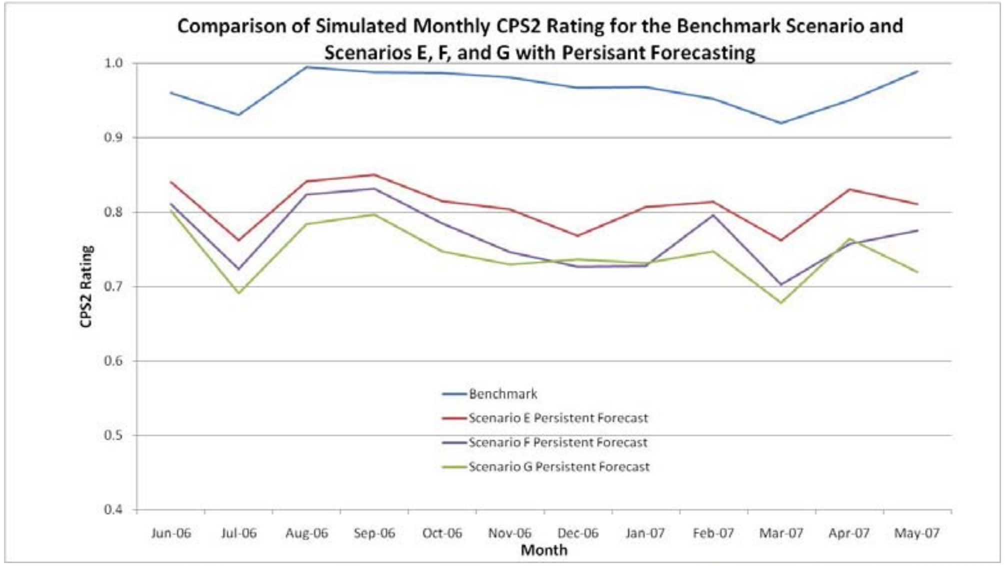
- Benchmark Scenario was established: historic wind development but current regulating capacity
- Proposed development scenarios: CPS2 rating decreases with increased wind power capacity



Part 2: NWE Dispatch Simulation

Dispatch Simulation Results

- Benchmark Scenario was established: historic wind development but current regulating capacity
- Proposed development scenarios: CPS2 rating decreases with increased wind power capacity
- Hypothetical development scenarios: CPS2 rating decreases with increased wind power regional concentration



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Part 2: NWE Dispatch Simulation

- Dispatch Simulation: Wind Forecasting Mitigation
  - Simulated incorporated three wind forecasting method
    - Persistent Forecast: average wind power for next dispatch interval equal previous interval
    - Persistent Ramp Forecast: change in average wind power to next dispatch interval equal to change to previous interval
    - Perfect Forecast: average wind power for next dispatch interval taken directly from simulated wind power time series

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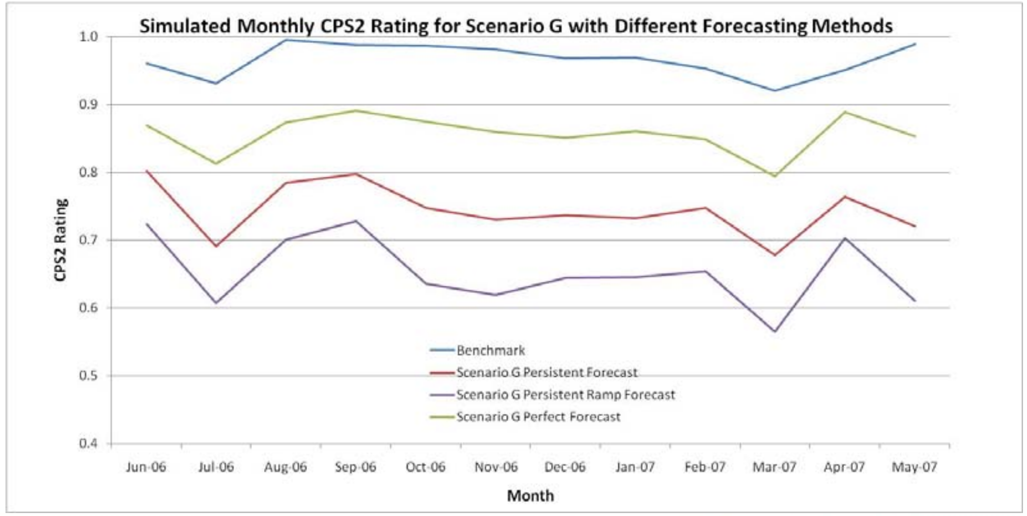
Part 2: NWE Dispatch Simulation

- Dispatch Simulation: Wind Forecasting Mitigation
  - General Result:
    - Perfect Forecast had best results in CPS2 rating
    - Persistent Forecast had next best results in CPS2 rating
    - Persistent Ramp Forecast had worst results in CPS2 rating



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Part 2: NWE Dispatch Simulation

Dispatch Simulation: Regulating Capacity Mitigation

- General Approach: Determine the increase in regulating capacity required to maintain certain CPS2 rating

Wind Scenario*	Factor of Current Wind Capacity	Factor of current RRR+ for CPS2 of at least 90% for all months	Factor of current RRR for CPS2 of at least 91% for all months	Factor of current RRR for CPS2 of at least 94% for all months	
A	1.00	1.00	1.00	1.44	122.4MW RRR
B	2.49	1.00	1.00	1.68	142.8MW RRR
C	5.15	1.36	1.56	2.15	
D	10.07	2.74	3.02	4.32	
E	10.07	2.54	2.73	4.05	
F	10.07	3.37	3.68	4.67	
G	10.07	3.84	4.12	5.44	

*For this analysis, wind scenarios were modeled with persistent forecasting method

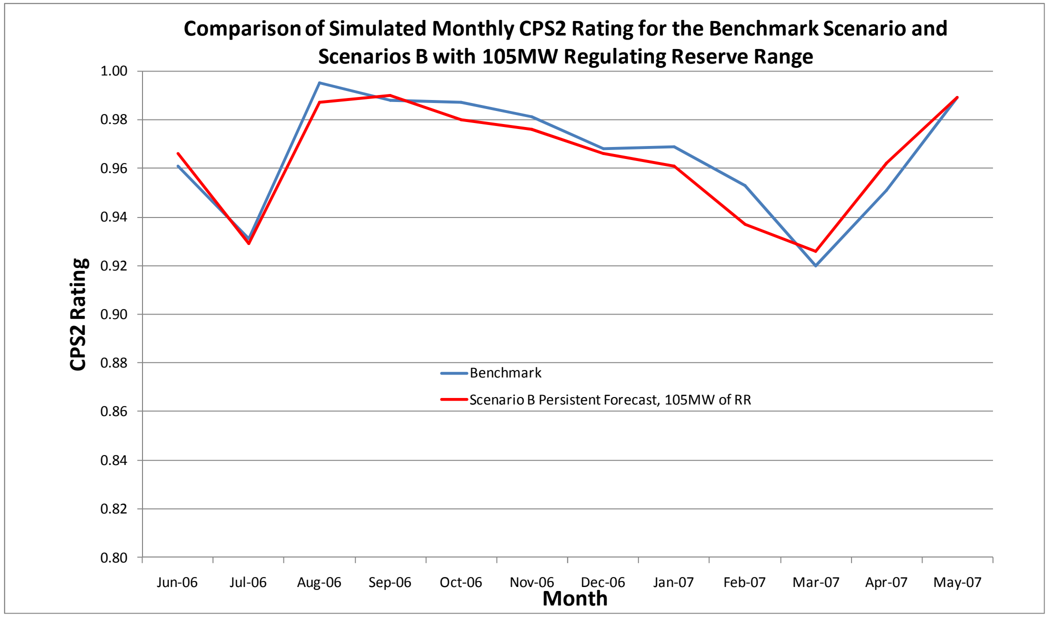
+RRR: abbreviation for Regulating Reserve Range. The current range for NWE is 85MW

- General Result:
  - Required additional RRR increased with increase of wind power capacity
  - Required additional RRR increased with increase of wind power regional concentration

Part 2: NWE Dispatch Simulation

Dispatch Simulation: Regulating Capacity Mitigation

- Sensitivity Analysis: CPS2 Rating for Scenario A with current RRR compared to Scenario B with +20MW RRR



- Caution: Required RRR increase for Scenario A to B growth may not be proportional for other growth increments

Conclusion

- Impact of wind development scenarios to variability
  - Variability in terms of magnitude increases with increased wind capacity
  - Variability in terms of percentage capacity decreases with increased wind capacity
  - Variability in terms of magnitude decreases with increased regional diversity for a constant wind capacity
- Impact of wind development scenarios to NWE system performance
  - CPS2 ratings decrease with increased wind capacity
  - CPS2 ratings increase with increased regional diversity for a constant wind capacity
- Impact mitigation methods
  - “Perfect Forecasting” was most effective in improving *simulated* CPS2 ratings
  - Additional RRR improves CPS2 ratings
  - Required additional RRR increased with increase of wind power capacity
  - Required additional RRR increased with increase of wind power regional concentration

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Moving Average Wind Speed

$$v_j = \frac{1}{N+1} \sum_{i=j-\frac{N}{2}}^{j+\frac{N}{2}} w_{i-j+\frac{N}{2}+1} v_i$$

$$N = T / \Delta t$$

v_j : j^{th} element of the moving average wind speed

v_i : i^{th} element of the original wind speed

w : normalized vector of length N+1, each element is the weight of the i^{th} element in moving average wind speed

N : number of points around the j^{th} included in each averaging process (even integer)

T : propagation time

Δt : time step in the original wind speed

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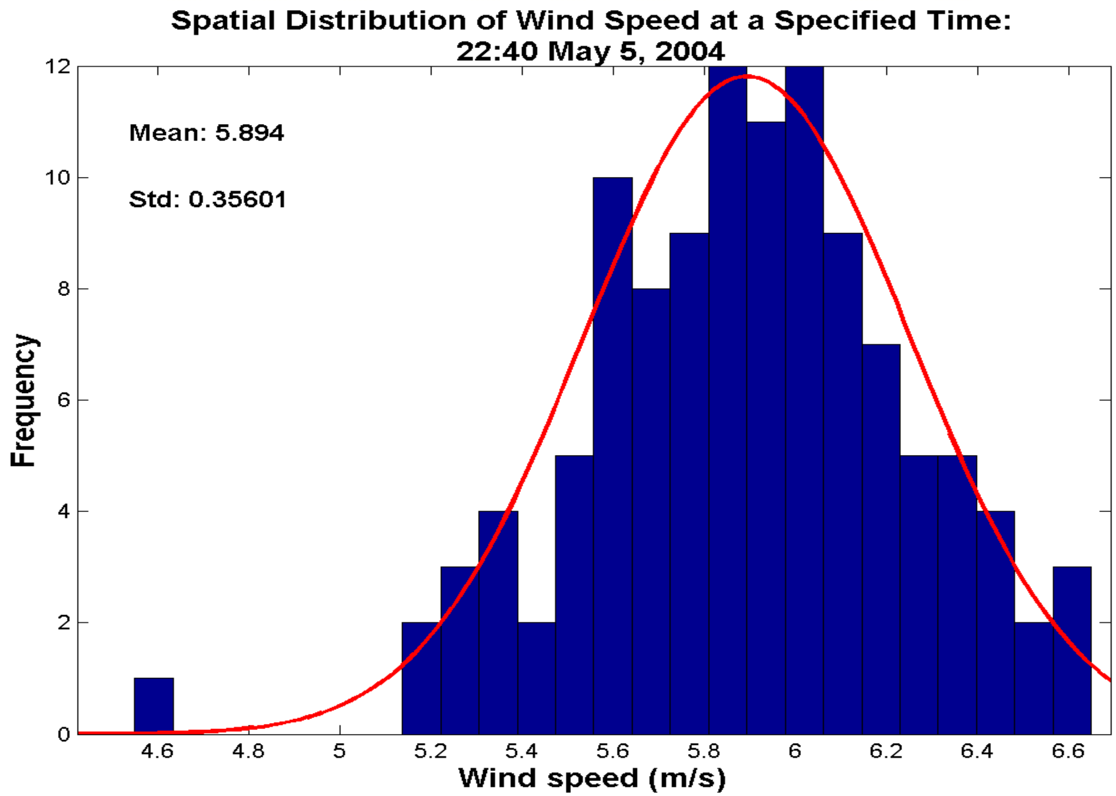
Spatial Wind Speed Distribution



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Multi-Turbine Power Curve

$$P_j^m = \sum_i P_{j+i}^s \times p_i^s$$

P_j^m : jth element of the multi-turbine power curve

P_{j+i}^s : (j+i)th element of the single-turbine power curve

p_i^s : probability of occurrence of the wind speed corresponding to the normal spatial distribution. Standard deviation of normal distribution is proportional to park dimension

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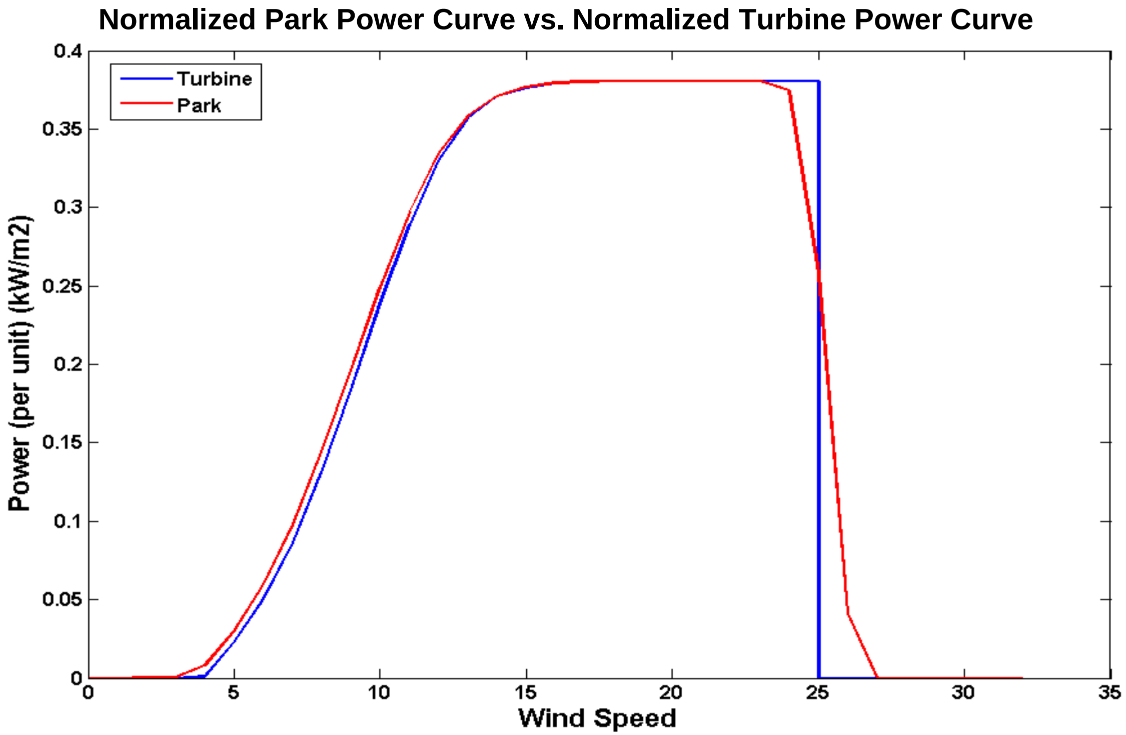
Multi-Turbine Power Curve



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1-Minute Model

- Procedure:
  - Take 10-minute wind power time series
  - Linearly interpolate two successive 10-minute wind power outputs
  - Introduce random perturbations
  - Random perturbations are 10 randomly generated numbers with a normal distribution and specified standard deviation
  - Specified standard deviation is one sixth of the difference between the two successive 10-minute power intervals (empirical value)

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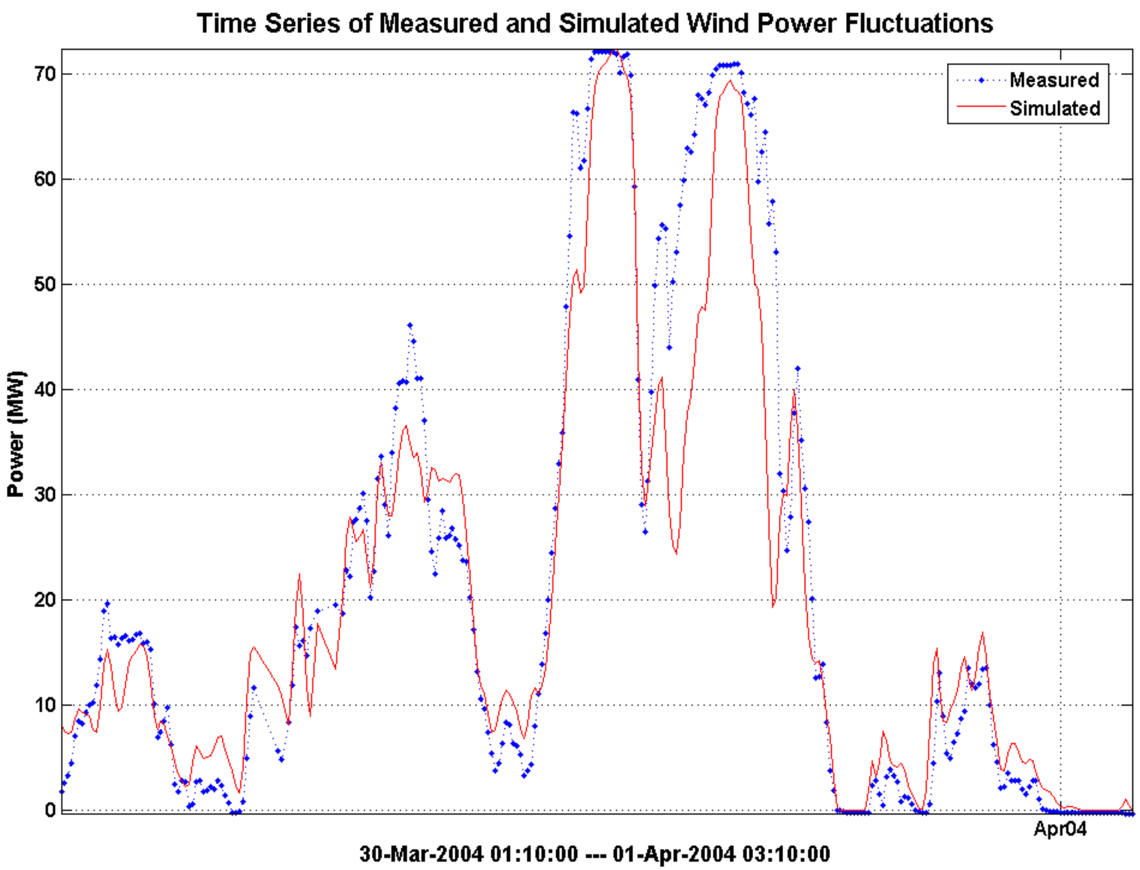
Facility Time Series Validation



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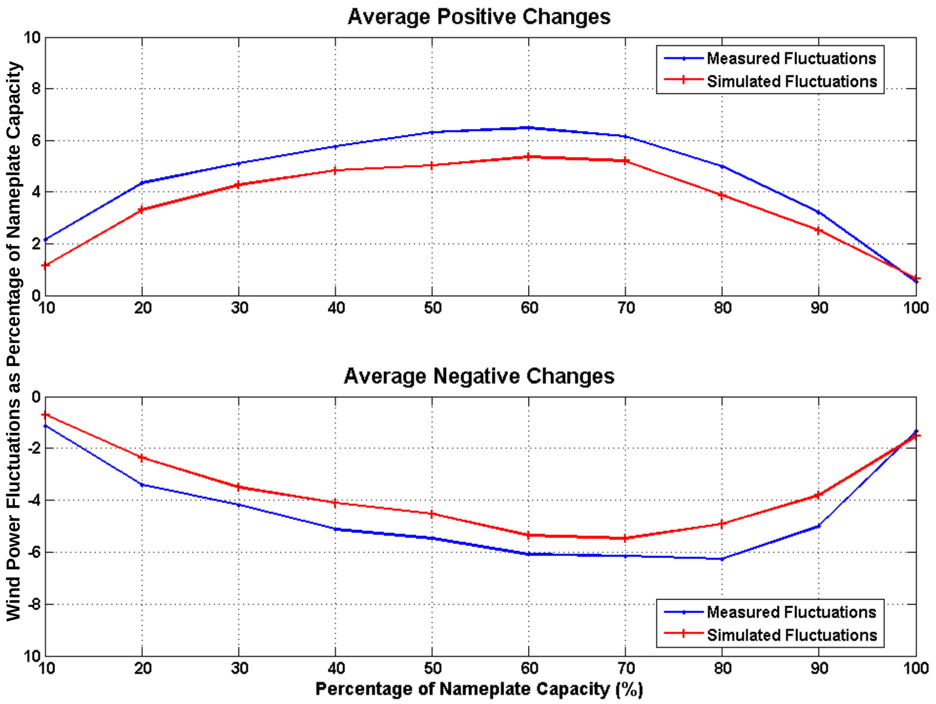
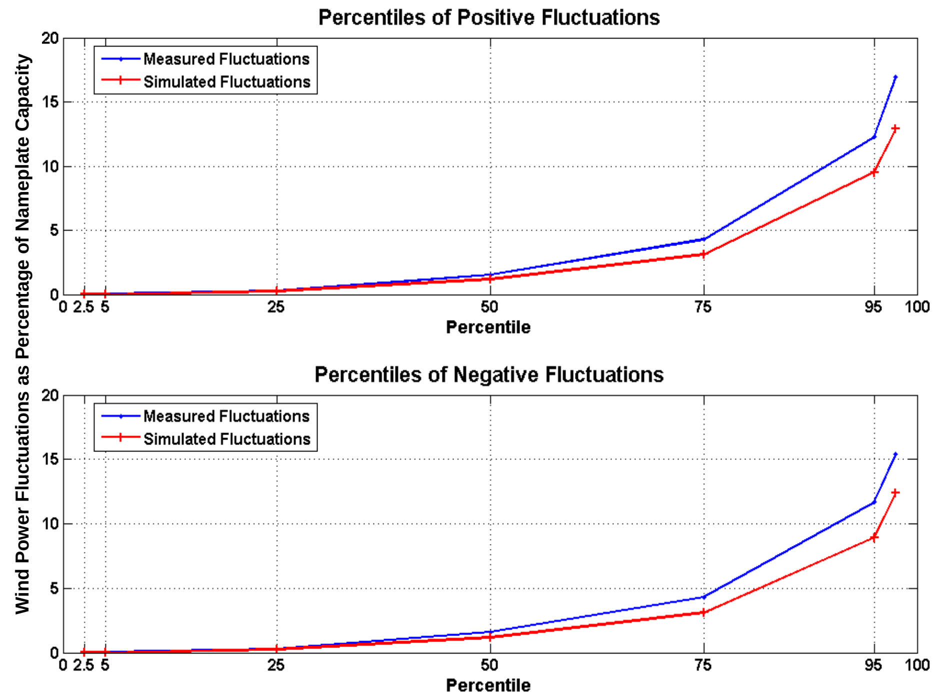
10-Minute Facility Fluctuation Validation





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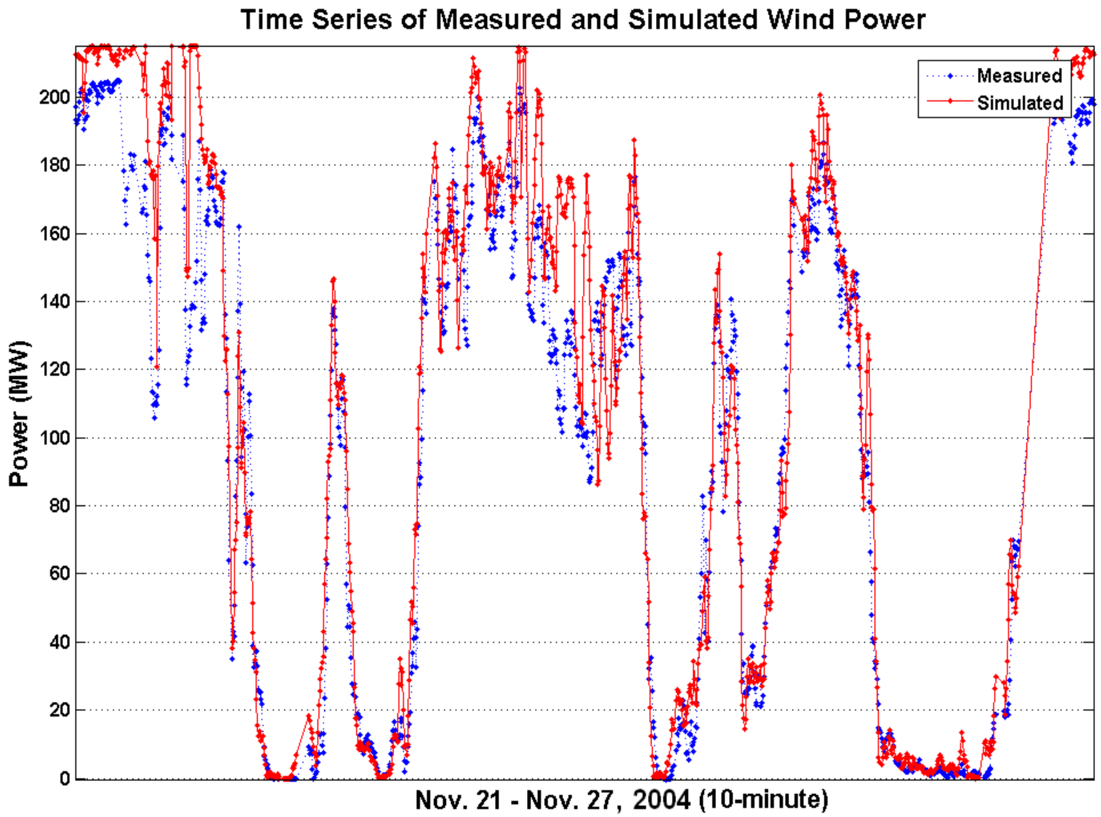
Regional Time Series Validation



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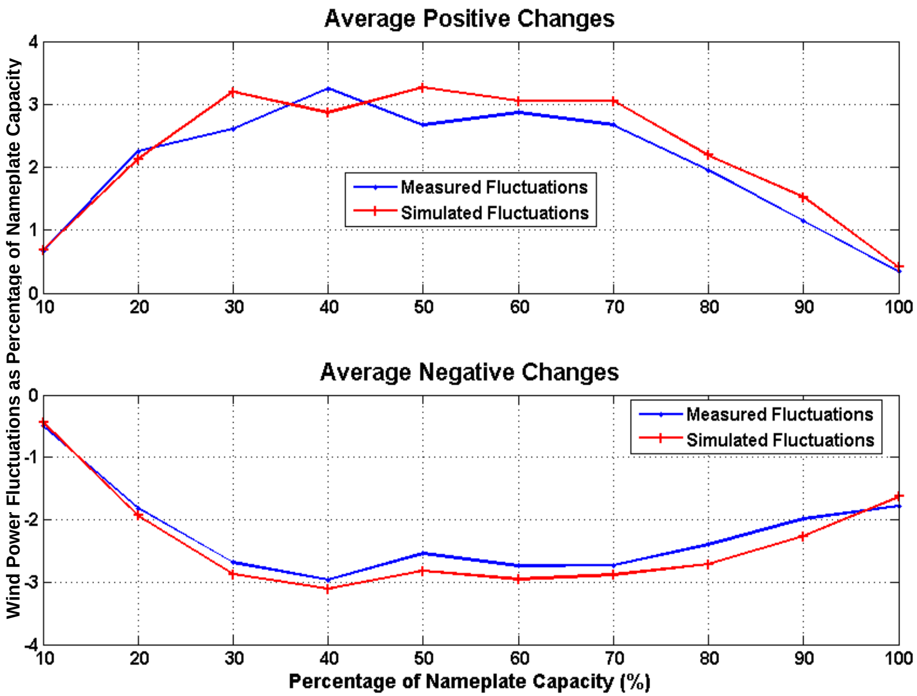
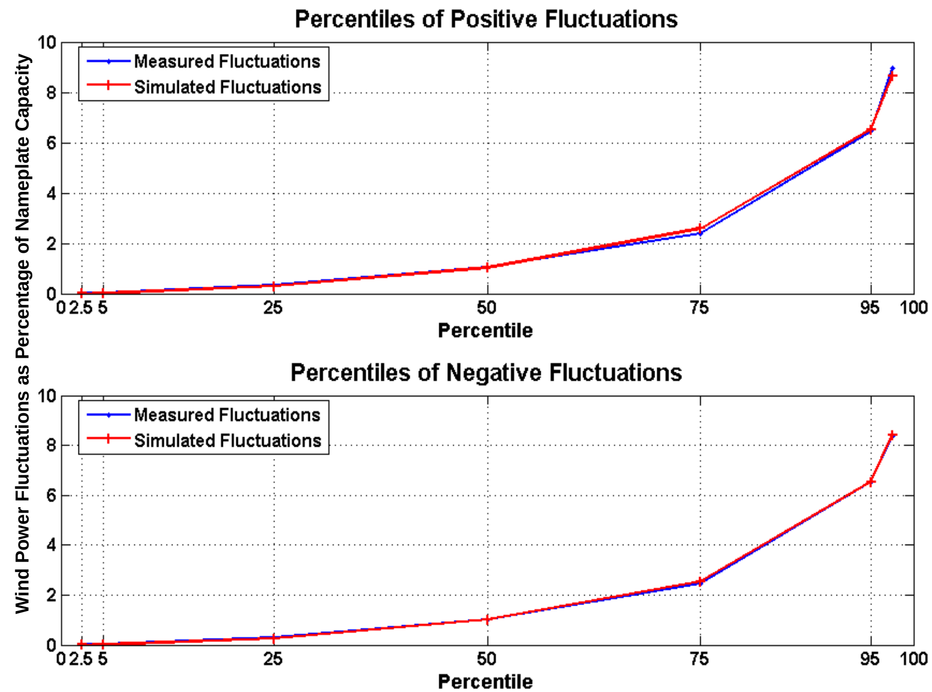
10-Minute Regional Fluctuation Validation





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Hypothetical Scenarios

Region	Scenario E	Scenario F	Scenario G
Region 1	362.5 MW	625 MW	100 MW
Region 2	362.5 MW	625 MW	1150 MW
Region 3	362.5 MW	100 MW	100 MW
Region 4	362.5 MW	100 MW	100 MW
TOTAL	1450 MW $\sigma=0$	1450 MW $\sigma=303$	1450 MW $\sigma=525$

Equivalent capacity to Scenario D

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Dispatch Simulation Model

Control decision every 60 minutes

Existing control deviation
- Current ACE
- Current RR usage

Expected Load change
- Day-ahead forecast

Interchange Schedule change

Expected wind generation
- Persistent wind forecast (no change in next 60 minute)
- Persistent ramping forecast
- Perfect point forecast

Decision for next 60 minutes

Control instruction threshold
If dispatch change within +/- 20MW, no instruction is made

1-minute simulation

Energy market response for each minute
- Ramping starts 10-min before the hour and ends 10-min after the hour and is subject to ramping limit
- Energy market then holds level for 40-min

Calculate the mismatch after dispatch
between the energy market dispatch and net demand (Load + Scheduled Interchange – Wind Generation)

Calculate required regulating reserve level
To balance the mismatch, subject to available regulating reserves (up & down) and ramping limit

Calculate the remaining mismatch
[energy market dispatch + regulating reserve dispatch] and [Load + Scheduled Interchange – Wind Generation] as **ACE** and the simulated interchange

Calculate operation reliability index: CPS2

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